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Woods Hole Oceanographic Institution

Report on the Office of Naval Research Shallow Water Acoustics Workshop
April 24-26, 1991

by

George V. Frisk

January 1992

Technical Report

Funding was provided by the Office of Naval Research
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TABLE OF CONTENTS

Abstract 1

Acknowledgements 2

Introduction 3

Executive Summary - Whither Shallow Water Acoustics? 5

I. The Seabed 9

II. The Water Column and Surface/Arctic 11

III. Analytic and Numerical Modeling/Ambient Noise 17

IV. Laboratory and Field Experiments/Signal Processing 21

Appendix A: Agenda 23

Appendix B: Attendees 25

Appendix C: Working Groups 29

ABSTRACT

The results of an unclassified Workshop on Shallow Water Acoustics, sponsored by the Office of Naval Research Code 1125OA, are presented. The workshop was held on April 24-26, 1991 at the Woods Hole Oceanographic Institution and included about forty-five scientists specializing in ocean acoustics, geology, geophysics, and physical oceanography. The goal of the workshop was to determine future directions for basic research in shallow water acoustics. This report summarizes the recommendations of the workshop and includes a synopsis of the deliberations of four working groups which focused on the following specific research issues: (1) the seabed, (2) the water column and surface/Arctic, (3) analytic and numerical modeling/ambient noise, and (4) laboratory and field experiments/signal processing.

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INTRODUCTION

On April 24-26, 1991, the Office of Naval Research Code 1125OA sponsored an unclassified Workshop on Shallow Water Acoustics at the Woods Hole Oceanographic Institution. The purpose of the workshop was to determine future directions for basic research in shallow water acoustics by assembling a group of about forty-five scientists specializing in ocean acoustics and related disciplines. Since the complexities of sound propagation in shallow water are influenced by both the seabed and the oceanography of the water column, the group included underwater acousticians, geologists, geophysicists, and physical oceanographers.

After about a day of tutorial talks, the large group broke up into four smaller groups in order to focus on specific research issues: (1) the seabed, (2) the water column and surface/Arctic, (3) analytic and numerical modeling/ambient noise, and (4) laboratory and field experiments/signal processing. These working group discussions were particularly stimulating because the workshop included applied as well as basic research scientists. On the last day, the working group leaders presented summaries of the deliberations within their groups.

This report is organized as follows. The Executive Summary constitutes my personal interpretation and synthesis of key themes which emerged during the workshop. Sections I-IV are summaries of the working group discussions which were written by the group leaders and subsequently edited by me. Finally, the Appendices describe the workshop agenda, the list of attendees, and the composition of the working groups.

EXECUTIVE SUMMARY

Whither Shallow Water Acoustics?

There are sufficient complications
to keep all modelers subdued.
David E. Weston [5]

What is shallow water acoustics and where is it going? Shallow water acoustics is a field which reflects both the best and the worst aspects of underwater acoustics research. On the one hand, it is a stimulating and exciting discipline to the physicist, the oceanographer, and the signal processor who are intrigued by the richness of a problem in which acoustic signals interact with an amazingly complex waveguide environment. From a different perspective, however, it represents a sloppy empirical approach in which, over the years, countless transmission loss measurements have been averaged in one variable or another so that some scientific conclusions, albeit crude, could be drawn. The latter approach, in fact, masks the delicate interplay between the acoustical physics and the ocean environment. In the future, this averaging process should be abandoned, and research efforts should concentrate on measuring and exploiting the sensitivity of the acoustic field magnitude *and* phase to the variability in the ocean environment.

How is shallow water acoustics defined? Shallow water acoustics suffers, to some degree, from an identity crisis which is due in part to the fact that a concrete definition of the field is elusive. Some would say that water depths less than one hundred fathoms (nominally the continental shelf break) are acoustically shallow. Yet, this definition ignores the fact that a critical parameter in describing waveguide propagation is the acoustic wavelength-to-water depth ratio. From that point of view, if the problem of a 50 Hz sound wave propagating in 100 m of water is treated as a shallow water situation, then the case of a 5 Hz signal in 1000 m of water should be dealt with in a similar manner. Others would claim that shallow water acoustics encompasses those circumstances in which a normal mode representation of the sound field is most appropriate. Yet, ray theory with beam displacement has been effectively applied to shallow water environments [1]. Perhaps the most pervasive characteristic of a shallow water acoustics problems is that it typically involves significant interactions with both the ocean surface and the bottom. This feature suggests that holistic solution techniques, that is, ones which embrace simultaneously the effects of the water column as well as the waveguide boundaries, are desirable. In deep water acoustics, it is much more common and appropriate to decompose the propagation problem into its constituent components; in that case, some of the elements, such as interaction with one or both boundaries, can sometimes be ignored.

The seabed is the king of the shallow water acoustics problem. Ever since the pioneering work of Pekeris [2], who first illuminated the complexities associated with the introduction of a penetrable bottom into the ocean acoustic waveguide, researchers have concentrated on the seabed as the dominant environmental influence in shallow water acoustics. The heterogeneous nature of the bottom, arising due to complex geological processes, is undisputed in coastal regions. Although deep water bottoms in the vicinity of ridge crests, for example, may be equally complicated geoacoustically, the waveguide effect in shallow water tends to amplify the bottom interaction effects. In addressing this problem, increasingly complex, horizontally stratified structures have been introduced, with a recent concentration on the behavior of shear waves [3,4]. It is clear that the next stage of the research should focus on a statistical characterization of lateral variability in bottom properties and their influence on the sound field in the water column.

The water column is the prince of the shallow water acoustics problem, waiting to assume the throne. Because of the apparent dominance of the seabed, there has typically

been only a modest amount of research activity addressing the effect of water column variability on shallow water acoustic propagation. A notable exception is a remarkable set of observations carried out by Weston *et al.* [5-10] in the Bristol Channel, southwest of the United Kingdom. These included measurements of the effects of wind, bubbles, tides, and fish shoals on the sound field, as well as observations of resonance effects in the ambient noise field. This work and that of Zhou *et al.* [11] on the resonant interaction of sound waves with internal waves in shallow water indicate that the water column can no longer be largely ignored in the shallow water acoustics problem. The internal waves ride on the surface mixed layer, which is the dominant stratification of the water column, and is therefore a prime candidate for careful examination. It is unlikely that the water column will ever assume the preeminent position of the seabed in shallow water acoustics. However, the acoustical oceanography of the water column offers some exciting physics problems and cannot be ignored in the development of a complete shallow water acoustics picture.

Both long- and short-term acoustic experiments, integrated with appropriate measurements of the environment, should be conducted. In the past, again because of the emphasis on the spatial variability of the seabed, shallow water acoustics experiments have been performed over relatively short periods (e.g., hours and days). The determination of the temporal effects of the water column, however, calls for longer term measurements (e.g., weeks and months). In this regard, the British paradigm of Weston *et al.* is a desirable one to emulate. For example, their measurements of wind effects on shallow water sound transmission [5] consisted of 2-3 day observations obtained monthly during the period May 1967-September 1969. Evidence also exists which indicates that, under certain conditions, even the seabed properties may vary seasonally due to temperature changes in the water column [12]. The complexity of the acoustical oceanographic interactions also suggests that sophisticated signal processing methods will be required in order to properly interpret these data with high resolution for both forward and inverse applications. It will be desirable to explore high resolution spectral estimation methods, which capitalize on suitable models for the shallow water acoustic signal. For example, in a range-independent environment, the normal mode decomposition naturally leads to a spatial signal model consisting of a sum of damped sinusoids. Appropriate signal models for more realistic, three-dimensional environments with temporal variability must also be developed. It is also clear that the experimental effort would benefit greatly from the selection of one or more testbeds or natural laboratories in which researchers could compare techniques, observations, and interpretations. In addition, laboratory experiments can serve to clarify the roles of the myriad of influences on the shallow water acoustic signal.

Both stochastic and deterministic modeling are essential to our understanding of shallow water acoustics. Shallow water waveguide physics presents an interesting, dichotomous challenge to the theoretical acoustician and modeler. On the one hand, the problem seems so complex that only a stochastic description seems appropriate. Certainly stochastic modeling, with calculations of higher order moments, should play a significant role in the interpretation of data as well as in predictive efforts. On the other hand, the shallow water environment exhibits various acoustical oceanographic effects of an apparently deterministic nature which may lend themselves to approximate analytic descriptions. For example, resonance effects occur repeatedly in the shallow water environment beginning with the normal modes themselves, which are natural resonances of the waveguide. In addition, as previously mentioned, acoustic/internal wave resonances [11] as well as resonant effects in the ambient noise field have been observed [10]. Thus, resonant behavior, which lends itself to analytic analysis, may be a key theoretical issue in the shallow water problem. In the case of both stochastic and deterministic methods, a holistic, full waveguide approach must be emphasized.

Summarizing then, some of the key recommendations regarding future directions for basic research in shallow water acoustics are:

- The shallow water acoustics problem involves an intricate interplay of acoustic interactions with the water column, the rough surface, and the heterogeneous bottom, and consequently its solution ultimately calls for a holistic approach.
- The shallow water environment is characterized by extreme variability, and therefore a statistical description of this complex medium and its influence on the statistics of the acoustic field are required.
- The role of water column variability (which has largely been neglected in the past) must be carefully addressed.
- In addition to the stochastic characterization, deterministic analyses should also be pursued in circumstances where they are appropriate, for example, in resonant acoustic/oceanographic interactions.
- There is a need for one or more testbeds or natural laboratories for conducting both long- and short-term acoustic experiments which should be combined with suitable measurements of the environment.

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I. The Seabed

The role of the seabed in bottom-interacting ocean acoustics is well established, and the definition of an accurate bottom model reflecting the full poro-elastic response is critical in shallow water propagation. The near-bottom sediments may consist of soft, recently deposited material or hard, lithified strata; however in most shelf deposits, the strata near the bottom are unconsolidated sands, silts, and clays with porosities less than about 60% and compressional wave velocities that increase more or less monotonically with depth, with impedance discontinuities at depths corresponding to major geological changes. Immediately beneath the seafloor the velocity gradients may be significantly larger than those used traditionally on the basis of extrapolations from deeper regions, and as a result, acoustic energy which enters the seafloor at low grazing angles may be reflected (scattered) in a manner significantly different from that which is predicted when a homogeneous layer or even a constant gradient is assumed.

In the last ONR shallow water Accelerated Research Initiative (cf. *ONR ARI Close-Out Report-Shallow Water Acoustics*, 30 June 1991), significant progress was made in learning to model and measure the geoacoustic properties of the seafloor, at least with respect to depth at fixed locations. Geoacoustic models based on the physics of water saturated, particulate media were formulated and tested, and several field techniques were developed for measuring geoacoustic properties *in situ*. Thus we graduated from empirical models based largely on data extrapolated from very high-frequency lab and field measurements to models more closely related to the geology and physical properties of the sediments.

During the performance of these earlier tests, all of which were done at sites where ground truth was available from prior borings and other investigations, it became clear that most of the shelf sediments were quite laterally inhomogeneous and that it would be necessary to incorporate some statistical measure of lateral variation rather than try to model these changes deterministically. Thus we feel that one of the main focuses of new work should be to determine the amounts of variability to expect both vertically and horizontally in the sediments. Tools developed in our prior work are available to begin these studies, and new surveying techniques based on towed arrays will be proposed to accomplish 3-D modeling in an efficient way over larger areas.

Because of the random nature of lateral inhomogeneity and temporal variations in the properties of the water column (and seafloor), we feel that it would be very advantageous to establish one or more "natural laboratories" at well-defined sites where various investigators may carry out experiments to test new concepts, or observe propagation characteristics at different times and under different conditions. The ground truth at these sites would be established with boreholes, and a number of techniques using both existing and proposed equipment would be used to establish lateral variability in detail. The proposed work includes the following:

(1) A 3-D survey using Huntec or similar gear to establish the stratigraphy and acoustic variation of the near-bottom sediments. This work has already begun and it clearly illustrates the variability of the seabed and the nature of the inhomogeneities that will produce scattering and loss of coherence in bottom-interacting acoustic signals.

(2) Surveys of smaller selected areas within the large test site to determine and quantify 3-D variation of the sediment geoacoustic properties. At the early stages, this work would be carried out using existing equipment and techniques which were developed during earlier work. Some examples include:

(a) The bottom source and multiple receiver arrays developed by Stoll (compressional and shear waves) and Ewing and Sutton (horizontally polarized shear waves).

(b) The bottom shear modulus profiling technique developed by Yamamoto et al.

(c) The synthetic aperture method developed by Frisk et al.

(d) The NOARL DTAGS and any other systems tested and ready to deploy.

At a later stage, a towed array, developed and tested while the above work was being carried out, would be used to obtain closely spaced (2.5 m) 1-D inversions over the site yielding a more complete 3-D geoacoustic model of the region. In addition to the tasks mentioned above, which focus on 3-D imaging, the following work is also felt to be important in furthering our understanding of geoacoustic modeling of the bottom:

(3) Studies of anisotropy in compressional and shear wave propagation which will be accomplished during the experiments using bottom deployed sources and arrays mentioned above.

(4) Studies of the effects of gassy sediments on acoustic propagation and the seasonal, biogenically controlled variability of gassy sediments.

(5) The improvement of inversion techniques designed to extract bottom models from acoustic data and conversely the design of improved experimental configurations to optimize the data used in these inversions.

(6) High-resolution cross-hole tomography using instrumented boreholes which will also provide the required ground truth in the area.

All of the above work must be done in close cooperation with researchers charged with modeling and measuring the spatial and temporal variability of the sound field in the water column as well as determining the various mechanisms which generate ambient noise and control the upper boundary and various internal inhomogeneities in the water column.

As a starting suggestion, we propose to work in the Hudson Canyon area where preliminary Huntec surveys have already been carried out. An area about 40 km $\times$ 40 km would be carefully chosen for the work described above. This area has been chosen not only because the work already done there would result in a considerable cost saving, but also because it is typical of many passive continental margins. Alternative sites in the Gulf of Mexico and the Pacific are also viable possibilities.

II. The Water Column and Surface/Arctic

Because this topic embraces a broad range of potential oceanographic influences on the acoustics, we systematically examined each coastal oceanographic process and forcing function and attempted to comment in each case on at least some of the following issues:

(1) *Oceanography*

(a) What aspects of the particular process are specific to shallow water?

(b) How well can the process be currently described, measured, modeled, and forecast by oceanographers?

(2) *Acoustics*

(a) How well can we model acoustic propagation through the oceanographic feature, particularly as a function of frequency, water depth, and source/receiver geometry?

(b) What are the temporal/spatial coherence effects of the feature on the acoustics?

(c) Can sound be used to invert for the oceanographic feature?

Finally, we comment on some experimental considerations.

Surface Gravity Waves

(1) Although many characteristics of surface gravity waves are well understood, they are still the subject of considerable investigation (e.g., the ONR SWADE Project). Some aspects specific to shallow water include the fetch-limited conditions, and the effects of bottom topography and currents in steepening, refracting, focusing, and altering the wavelength of the waves. Numerical wave models (e.g., WAM), which accommodate wind and topography (but not current) inputs, perform fairly well. A variety of methods exist for measuring directional surface wave spectra, including synthetic aperture radar (SAR), wave buoys, and pressure gauges. However, whether these techniques provide adequate resolution for acoustic field prediction is unclear.

(2) Although considerable research effort has been expended on acoustic surface scattering, its effect on the spatial and temporal coherence of the sound field is not well understood. Even for small roughnesses and low frequencies, the large number of surface interactions per unit length of propagation in shallow water tends to magnify any potential effects. This behavior is further influenced by the nature of the sound velocity profile in the water. Acoustic inverse methods for inferring the surface wave spectrum have been developed (cf. Miller, Lynch, and Chiu; Brill, Rubenstein, etc.).

Bubbles

(1) The bubble layer is related to the development of seas, specifically plunging and spilling breakers, a process which is more difficult to model in shallow water. Simple 1-D models of the bubble layer structure exist (cf. Farmer and Crawford, Wu, etc.) and should be extended. Techniques under development to measure the bubble layer include upward-looking sonar and Medwin's drifter system.

(2) Acoustic interaction with the bubble layer is an important research issue, since the layer forms a low-velocity region near the surface which can both duct and scatter the acoustic energy.

Langmuir Circulation (Windrows)

(1) Windrows line up parallel to the wind, and in shallow water, their spacing is approximately three times the water depth. Langmuir cells can carry bubbles as well as temperature and density structure downward. They are intermittent, not easily predictable, features.

(2) Their effect on acoustics is unknown, and only oceanographic measurements associated with Langmuir circulation have been conducted to date.

Internal Waves

(1) Internal waves are as common as surface waves, with a very different character in shallow versus deep water. The broadband Garrett-Munk spectrum is not appropriate in shallow water; instead narrowband spectra characterized by soliton propagation, are often observed. The nature of the internal wave spectrum will depend on the generation mechanisms which are locally important. Tides and bathymetric variability appear to play a major role in soliton generation, a process that has a more intermittent, deterministic character than that associated with the stochastic Garrett-Munk spectrum in deep water. Shallow water internal waves can be predicted with some success using, for example, a two-layer model (a mixed layer overlying a cooler denser layer). They also reflect from coastlines and modulate the surface, producing beautiful SAR images. Their wavelengths vary from a few hundred meters to many kilometers, with periods ranging from twenty minutes to twelve hours (the inertial period).

(2) The study of sound propagation through internal waves in shallow water is still in its infancy, with some interesting initial results having been produced by Zhou, Rubenstein, and Shmelerv. Internal wave effects appear to be negligible in many areas in winter, when the water is completely mixed, whereas strong effects occur in summer, when the mixed layer is less than the water depth. Spatial and temporal coherence effects are observed directly in the acoustic wavefront maps produced by Rubenstein and Shmelerv. When an acoustic source or receiver moves through the internal wave field, high-frequency fluctuations can result and may be appreciable over the temporal averaging times for signal processing algorithms. Zhou's work on resonant interaction of sound waves with internal waves shows that both acoustic wavelengths and ray/mode cycle distances are important length scales to consider in scattering from oceanographic features. The relationship of these acoustic scales to the scale of an ocean object may be critical, and for example, can cause the sound field to be particularly sensitive to certain spectral components of the internal wave field. The continuous-wave results of Rubenstein and Shmelerv, as well as the tomographic results of DeFerrari, indicate that acoustic measurement of the internal wave field may be possible over a large area.

Mesoscale Large Scale/Coastal Oceanography

(1) The gross behavior of these features, which include fronts, eddies, squirts, and jets, can be modeled and predicted reasonably well. Their characteristics are easier to forecast in shallow water than in deep water because topography (which is sufficiently well known for physical oceanographic purposes) controls many of them. A full predictive capability of the larger scale structures (e.g., jets and eddies) does not exist, but the locations and times which are favorable for feature formation can be predicted. Also, the fine-scale structure of the larger objects is not well described. This is an active area of physical oceanographic research.

(2) While the problem of acoustic interaction with the large-scale deterministic structures is under control, acoustic scattering from the fine structure is not well understood. If this fine structure matches the acoustic wavelength or mode cycle distance, then scattering of sound may be enhanced, as discussed for internal waves.

Upwelling

(1) The conditions, mechanisms, and geographical areas of importance for upwelling are very well known. It is very important in determining the temperature structure, for example, along the California coast.

(2) The acoustic effects associated with upwelling behavior have not been measured. As with the larger scale oceanography, we can probably describe the large scale behavior well, but are not sure of fine scale effects.

Tides

(1) The level, phases, and periods of tides are very well known and represent some of the earliest oceanography. Tidal currents (which generate internal waves, etc.) are more difficult to predict, but are important. Tides can advect fronts about 10 km every tidal period.

(2) Even simple tidal changes can affect the overall acoustic structure in shallow water with even more drastic effects over rough bottoms. A detailed theoretical and experimental study of the relationship between tidal excursions and the behavior of the acoustic field has never been conducted.

Surface Mixed Layer

(1) A good modeling and predictive capability exists for the surface mixed layer. Since it is the dominant stratification of the water column, it is perhaps the critical feature coupling the physical oceanography to the acoustics.

(2) Internal waves ride on the surface mixed layer, which can refract and reflect sound across its interface and potentially cause significant acoustic mode coupling effects. However, acoustic interaction with the mixed layer is not well understood.

Bottom Boundary Layer

(1) A good modeling and predictive capability (e.g., the Grant/Madsen wave current model) as well as good measurements (e.g., the STRESS and CODE experiments) exist for the bottom boundary layer. The temperature and density stratification may be small as compared to the stratification in the surface boundary layer. However, stronger effects may be present due to slope/shelf water intrusion effects.

(2) The effects of temperature and density stratification are negligible for acoustics, even at high frequencies. Although the effects of suspended sediments can be seen at high frequencies (above 100 kHz), it is doubtful that there is any effect at low frequencies (due to the difference in sound speeds between the water and suspended mass); however, this is not known conclusively.

Buoyancy Driven Flows

(1) River outflows (which can cause significant stratification many kilometers offshore, e.g., the Amazon and Yellow Rivers), rain, evaporation, and chimney convection of surface water are some of the mechanisms associated with buoyancy driven flows. Wind and tides dominate coastal flow models, which do not presently include buoyancy flows (a difficult, nonlinear problem).

(2) The degree of advection of the temperature and salinity fields and its effect on the acoustics are not known. However, the acoustics will be much more sensitive to temperature differentials, and we should therefore concentrate on understanding that part of the buoyancy signal.

Microstructure

(1) Turbulence mixes the water column, causing changes in density and buoyancy frequency.

(2) Acoustic scattering off microstructure tends to be a high-frequency (above 1 kHz) effect which is understood moderately well.

Coastal Meteorology

(1) The meteorology is harder to predict in coastal regions than in deep water areas. The VAST panel (J. Overland et al.) is addressing meteorological issues for coastal oceans.

(2) The difficulty in predicting coastal weather patterns contributes to the stochastic nature of the acoustic problem as well as the complexities of experiment design and execution.

Biology

(1) Upwelling, for example, moves nutrients upward in the water column and thereby attracts fish, marine mammals, and fishermen.

(2) This biological activity increases ambient noise and causes acoustic scattering, effects which are only moderately well understood.

Arctic

(1) Both fast ice and MIZ ice are found in shallow water. The MIZ ice can adhere to topographically driven fronts (e.g., the polar front in the Barents Sea in summer). The physical oceanographic changes due to brine rejection (ice freezing), for example, can be different in shallow water.

(2) Considerable work remains to be done on the problem of acoustic propagation in a waveguide with total or partial ice cover.

Experimental Considerations

It is clear that a diversity of oceanographic effects must be studied in order to fully understand the shallow water acoustics problem. Perhaps the most important is the mixed layer, simply because of its pervasive character in shallow water and its direct impact on other features such as internal waves and upwelling. However, the influence of bubbles, tides, and an Arctic ice canopy on acoustic waveguide propagation also cannot be ignored. Some of the experimental considerations in studying the oceanographic/acoustic coupling, which are unique to the shallow water environment, are:

- Potentially significant oceanographic influences on the acoustics occur over a spectrum of time scales ranging from minutes and days to weeks and months. Therefore both short- and long-term experiments are required, including seasonal experiments which would contrast the effects of stratified versus unstratified conditions at the same site.
- A broad range of meteorological forcing functions (e.g., winds, insolation) must be encompassed by the experiments.
- The role of topographic variability must be properly addressed, since it has ramifications for both the oceanography and the acoustics.
- The degree to which oceanographic effects influence acoustic bottom interaction in shallow water should be carefully examined.
- In the final analysis, the relative magnitudes of oceanographic versus bottom effects should be evaluated.

III. Analytical and Numerical Modeling/Ambient Noise

The problem of underwater acoustic modeling in a shallow water environment involves acoustic propagation, scattering, reverberation, volume scattering, and noise in a shallow waveguide. This problem is different from the deep water scenario in that the effective waveguide consists of the sea surface boundary, the water column, the ocean bottom and subbottom - all acoustically coupled. Unlike deep water acoustics, this coupling makes modeling isolated mechanisms difficult. Most important, in attempting to understand the shallow water acoustics problem, it is undesirable to model isolated events since the waveguide "molds" the acoustic signal and couples it to the waveguide environment and boundaries. The modelling effort should consider the whole problem, and simplifying assumptions, such as plane wave ensonification, are not appropriate.

Acoustic models should be used for preassessment simulations prior to final selection of the experiment site(s) and to identify important parameters to be measured. Modeling can be useful in discriminating the acoustic signal form the noise and interference. Difference in correlation modeling should be exploited here. The signal processing area is the place to measure these effects and determine their significance. All of the modeling effort supports and feeds into the signal processing effort.

Each of these points are discussed below in more detail.

Propagation

Extracting another 1/2 dB accuracy from present propagation models is not worth the investment. What is needed are 2-D and 3-D canonical benchmark analytic and numerical models and solutions by which to make useful comparisons with data and to validate more general shallow water models that may be developed.

Coherence modeling, i.e., computation of higher order moments vis a vis boundary conditions, is needed. Two-point correlations function models with appropriate boundary conditions have not been fully developed. The boundary conditions for such models have not been validated. Such theoretical developments have been attempted for deep water (McCoy, Beran, Berman, Baer, Flatte, and others), but have not always agreed. The need exists for further development of such numerical and analytic approaches in shallow water environments.

Cross-slope and diagonal-to-upslope analytic models are needed. These models should include penetrable ocean bottoms with density and sound speed contrasts. Present modeling attempts have allowed density contrast but not both density and sound speed contrasts.

There are a number of other requirements for shallow water propagation models:

- Near- and far-field capabilities.
- Both time- and frequency-domain algorithms.
- Range-dependent environments must be included.
- Realistic acoustic sources (e.g., pulses) should be used, as opposed to the customary CW point sources.

Seismic effects with poro-elastic properties and sediment anisotropy must be included in the models. Otherwise the ocean bottom and subbottom properties will not be properly included. At low frequencies, the whole ocean (sea surface to ocean basement) can be considered as part of the waveguide.

Stochastic vs. Deterministic Models

The need for stochastic models has been described above. This is predicated on the close coupling between water column environmental variability, rough stochastic boundaries, and inhomogeneous ocean bottoms and subbottoms. While the usefulness of deterministic models in shallow water analysis is certainly acknowledged, it is nevertheless felt that higher moment acoustic models hold the greatest potential for viable shallow water acoustic predictions.

Scattering and Reverberation

Perturbation approaches exist, but scattering off high roughness boundaries in a waveguide is a difficult problem to model and needs to be included as part of the boundary value problem. A 3-D perturbation theoretical treatment is needed.

Approaches that use plane wave assumptions are too simplistic and will not adequately include scattering from the waveguide with rough boundaries. Again, it is noteworthy to reiterate that the whole picture must be treated - scattering coupled to the waveguide.

The prediction of the scattered field alone may not be sufficient for signal processing applications. Moments of the scattered field are also needed for signal processing.

The shallow water waveguide "molds" the sound field. This is different from the deep water problem where a point source signal may be used, and isolated features, such as sea surface scattering, may be modeled as a distinct entity. Extraction of the signal from the interference is much more difficult in shallow water than in deep water. In shallow water, the problem of reverberation is one of almost continuous reverberation.

Attenuation and scattering are both loss mechanisms with respect to the propagated acoustic field. However, they are two distinctly different mechanisms and neither should be ignored. Both need careful consideration with regard to how they are modeled. Within the framework of scattering and reverberation modeling issues, the following have been highlighted:

(1) *Sea Surface Boundary Scattering*: The issues of bubble layers and their contribution to absorption, scattering, and reverberation in shallow water need to be addressed. Are bubbles in shallow water, and the type of scattering they produce, different from their counterparts in deep water?

(2) *Ocean Bottom Boundary Scattering*: The ocean bottom is always penetrable by the acoustic field. Therefore, the problem of bottom material scattering must be considered. The three-dimensional inhomogeneities in the ocean bottom and subbottom should be included in shallow water modeling.

(3) *Volume Fluctuations*: Internal waves in shallow water are different from internal waves in deep water. Shallow water internal waves are more correlated (ordered). Can the effects of shallow water internal waves be treated as mode coupling? Some evidence suggests this, but how shallow internal waves should be modeled to correctly include their effects on acoustic scattering and reverberation is not yet known. More experimental data is needed on this phenomena before it can be correctly included in acoustic models. These data should include environmental measurements on the internal waves as well as simultaneous acoustic measurements.

(4) *Volume Scattering*: Biologics in shallow water cannot be ignored. They pose a potentially serious scattering and apparent attenuation problem. Their collective reverberation signal may appear more like a false alarm target than reverberation from the shallow water boundaries.

Any biologics that contain or produce gas bubbles fall within this category. Fish schools have a doppler width associated with their acoustic scattering, and this may be exploited to provide identification and discrimination.

(5) *Three-Dimensional Scattering Models*: The discussions on shallow water acoustic models thus far have included the need for both 2-D and 3-D models. However, 2-D models cannot accurately track out-of-plane scatter and refraction. Very few 3-D underwater acoustic models exist. Those that do exist are still undergoing refinements and verification. The need for more development of 3-D broadband shallow water acoustic models, applicable to a dispersive waveguide, should be encouraged.

Ambient Noise

Distributed surface noise models exist (e.g., adiabatic mode models, parabolic equation, and fast-field programs with elastic bottoms), but the need exists for 3-D analytic and numerical noise models. Experiments need to consider the noise problem. Man-made versus natural noise sources are important. Man-made sources of noise in shallow water regions couple to deep water regions; the coupling of noise between these two regions may be a fruitful area of research. In shallow water, the noise is correlated with the waveguide and less isotropic than it is in deep water. Environmental "noise" created by Navy sources should not be ignored. The cross-spectral density, interferences, etc. referred to in the paragraphs on reverberation also apply to shallow water noise.

Scattering from an Object in a Waveguide

The close proximity of the boundaries makes the modeling of scattering from an object in a waveguide (including the bottom) a very difficult, self-consistent problem in modeling. There has been work done using Kirchhoff and Born approximations, but the fundamental coupling of the object and waveguide into a fully coupled model has not been verified, either in deep water or in shallow water. The need exists for experimental data, so that the precise behavior of the acoustic field in the presence of the waveguide boundaries and shallow water environment can be studied.

Models for Experiment Preassessment-Postassessment

Underwater acoustic models are typically used by experimentalists as part of their post-exercise analysis. This has proved to be very useful, if not sometimes frustrating. Shallow water acoustic models should also be used in experiment preassessment and planning. Proper use of such models can assist in identifying important parameters to be measured and in selecting experiment sites.

Signal Processing

Plane wave beamforming is not likely to be useful in shallow water signal processing. Accurate shallow water models could be extremely useful in identifying the acoustic signal from the noise and other interferences. Difference in correlation modeling should be exploited here. Signal processing is the place where the significance of the shallow water effects are determined; boundary effects, environmental focusing, etc. can all be quantified by signal processing. All of the modeling efforts discussed above support and feed into the signal processing effort. A strong relationship exists between signal processing and inverse methods. This should be supported in the shallow water efforts, and further development of inverse methods and models, together with their connection to signal processing, is encouraged.

IV. Laboratory and Field Experiments/Signal Processing

It was felt that the focus of experimental research should address the influence of small scale spatial and temporal environmental heterogeneity on the spatial and temporal statistics of the acoustic field in shallow water. The measurement program should work synergistically with the modeling efforts in the following ways:

(1) The modeling should guide the selection of candidate environmental forcing functions of acoustic field fluctuations and should guide the selection of spatial and temporal sampling parameters.

(2) The measurements should provide a challenging test of the predicted coupling between statistics of the environment and the statistics of the acoustic field, but should not overwhelm the models with complexity. It is expected that this criterion will constrain the acoustic frequency range.

(3) The measurement site should be chosen to provide a challenging but manageable complexity for model testing.

(4) While Monte Carlo simulations using deterministic models may provide some guidance on the statistical influence of environmental heterogeneity on the moments of the acoustic field, it is highly desirable to have models which address the propagation of statistical moments, i.e., which accept statistical moments of the environmental parameters and produce statistical moments of the acoustic field. It is anticipated that a complete, deterministic specification of the environment during field tests may require an unreasonable sampling density, whereas the measurement of statistical moments of the environmental forcing functions might be done with a reasonable number of instruments.

Three specific candidate topics for investigation are: (1) the loss of coherence in a signal field propagating in a random medium, (2) low-angle scattering by the ocean bottom, and (3) the role of scale model experiments.

Correlation Loss Due to Random Medium Influences

It is expected that the higher-order moments of the acoustic field which are driven by coupling of the time-dependent water column and the rough ocean boundaries might fall into two classes: (1) those, such as temporal coherence loss, which might be expected to grow as the propagation distance through the random medium increases, and (2) those that may saturate or even decrease as range increases due to "re-cohering" of the signal field by waveguide confinement and mode stripping. The former of these was discussed in more detail than the latter.

It is believed that environmental characterization provides a more difficult measurement challenge than the acoustic field measurements per se. This topic may provide a good opportunity to employ models which directly express acoustic field statistics in terms of moments of the environmental forcing functions. It is also probable that the complexity of the problem will increase rapidly with increasing acoustic frequency for a given environment, so the investigation can be readily swept through a broad range of challenges to acoustic models by changing the acoustic frequency.

Low-Angle Bottom Scattering

This investigation would have as its goals the determination of the physical mechanisms (e.g. boundary roughness, volume scattering within the bottom) responsible for low angle ($< 5°$) bottom

scattering, and the determination of scattering amplitudes for bistatic geometries. Because the nature of the continental shelf sediments is different from those found in the deep ocean, it is felt that deep water measurements might not be directly applicable here. The proximity of the ocean surface and the short arrival times of the fathometer returns from it introduce a measurement challenge for low grazing angle measurements. This difficulty was not solved at the workshop, but the possible use of synthetic bottoms in high-frequency scaled experiments and the scaling of higher-frequency in-situ measurements were suggested as possible approaches to making scattering strength measurements.

A wide variety of acoustic experiments in shallow water have shown that significant energy is scattered from the bottom back in the direction of the source, giving rise to high reverberation levels. The characterization of this bottom reverberation requires precise knowledge of the boundary scattering function at small grazing angles for both monostatic and bistatic geometries. Such knowledge presently does not exist. Moreover, where observations exist for higher grazing angle geometries, investigators have been unable to relate the measured reverberation levels to parameters of the sea floor in a causal manner. Accordingly, the goal of this measurement effort would be to extend current observations to grazing angles between 0 and 5 degrees with the bottom, to quantify the scattered field for horizontal and vertical bistatic angles, and to develop scientific understanding which permits the measured scattering to be causally related to specific properties of the seabed and/or the volume of marine sediments underlying the sea floor. While major emphasis would be placed on characterization of the scattering for acoustic frequencies between 200 Hz and 5 kHz, measurements would be performed up to 25 kHz both to compare results with the large body of higher frequency and grazing angle data that presently exist and to examine regimes where the causal mechanisms may be different. The acoustic portion of the experiment will probably require a field of receiving elements/arrays that can sample multiple bistatic angles. A low frequency parametric source may be required to eliminate scattering to the receivers caused by source minor lobes and facilitate multiple frequency sampling. Precise physical and acoustic characterization of the seabed in the vicinity of the scattering patch will also be required.

Scale Model Experiments

One of the major problems in shallow water is the difficulty in environmentally sampling the ocean in sufficient detail to provide the necessary inputs to numerical models. This leads to the common problem that there is insufficient background data to understand the measurements. This suggests two alternative approaches. The first is to consider the ocean as a stochastic medium with statistically known properties and bounded transmission loss characteristics. However, this approach does not give much insight into identifiable phenomena such as propagation around features, over uneven bottoms or through internal waves. These effects can cause temporal and spatial variability which must be built into any stochastic or deterministic model. To understand these phenomena in isolation, laboratory measurements have an important role to play. The small-scale experiment can provide scaling laws and insight, and can be used to check theoretical explanations and tests on measurement techniques. In order to understand the scientific issues of underwater sound propagation, the study of idealized problems of this type is important.

Recent examples of laboratory tests which have provided insight into underwater acoustics include propagation over rough interfaces, ambient noise generation, across-slope and downslope propagation, and shear wave propagation in sediments with cracks. More studies of this type, especially linked with studies of oceanographic events such as internal waves and ocean climates, will be useful in the future.

APPENDIX A

ONR SHALLOW WATER ACOUSTICS WORKSHOP

AGENDA

WEDNESDAY, 24 APRIL 1991

0800 **REGISTRATION AND CONTINENTAL BREAKFAST**
Carriage House

0900 **WELCOME AND INTRODUCTION**
George Frisk and Paul Boutin
Woods Hole Oceanographic Institution
Marshall Orr, *Office of Naval Research*

0930 **DIRECTOR'S WELCOME**
Craig Dorman, *Woods Hole Oceanographic Institution*

1000 **"SHALLOW WATER ACOUSTICS RESEARCH NEEDS: AN APPLIED PERSPECTIVE"**
Bernard Cole, *Naval Underwater Systems Center*

1040 **"A SELECTIVE REVIEW OF ACOUSTIC SHALLOW WATER THEORY AND EXPERIMENT"**
William Kuperman, *Naval Research Laboratory*

1120 **"GEOACOUSTIC MODELING OF THE SEAFLOOR IN SHALLOW WATER"**
Robert Stoll, *Lamont-Doherty Geological Observatory*

1200 **LUNCH - Carriage House**

1300 **"INVERSION FOR GEOACOUSTIC PARAMETERS IN SHALLOW WATER"**
Subramaniam Rajan
Woods Hole Oceanographic Institution

1340 **"NUMERICAL MODELING OF SEISMO-ACOUSTIC WAVE FIELDS IN SHALLOW WATER"**
Henrik Schmidt, *Massachusetts Institute of Technology*

1420 **"SPATIAL AND TEMPORAL VARIABILITY IN THE WATER COLUMN IN SHALLOW WATER"**
W. Rockwell Geyer, *Woods Hole Oceanographic Institution*

WEDNESDAY, 24 APRIL 1991 (cont.)

1500 **"RESONANT INTERACTION OF SOUND WAVES WITH SOLITARY INTERNAL WAVES IN SHALLOW WATER"**
Jixum Zhou, *Georgia Institute of Technology*

1540 **"ADAPTIVE ACOUSTIC PROCESSING IN SHALLOW WATER"**
Stephen Wolf, *Naval Research Laboratory*

1620 **SELECTION OF WORKING GROUPS**

1700 **RECEPTION - Fenno House**

1800 **DINNER - Fenno House**

THURSDAY, 25 APRIL 1991

0800 CONTINENTAL BREAKFAST - Carriage House

0840 "THE DARPA ADVERSE ENVIRONMENT INITIATIVE"
"A SHALLOW WATER ACOUSTICS EXPERIMENT ON THE NEW JERSEY CONTINENTAL SHELF"
William Carey, *Naval Underwater Systems Center*

0920 WORKING GROUP DISCUSSIONS

1200 LUNCH - Carriage House

1330 WORKING GROUP DISCUSSIONS RESUME

1700 RECEPTION - Clark Laboratory - 5TH Floor

1800 DINNER - Clark Laboratory - 5TH Floor

FRIDAY, 26 APRIL 1991

0800 CONTINENTAL BREAKFAST - Carriage House

0900 WORKING GROUP REPORTS

1200 LUNCH - Carriage House

1300 WORKING GROUP REPORTS

1400 SUMMARY & CONCLUSIONS

APPENDIX B

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APPENDIX C

ONR SHALLOW WATER ACOUSTICS WORKSHOP

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Group I	Group II	Group III	Group IV
The Seabed	The Water Column and Surface/Arctic	Analytic and Numerical Modelling/ Ambient Noise	Laboratory and Field Experiments/Signal Processing
Carriage House	*Clark 323A*	*CRL*	*Clark 519*
Badiey[1]	Duda	Baer	Carey
Doutt[4]	Feden	Chin-Bing*	Cole
Ewing	Geyer	Deane	DeFerrari[3]
Kravitz	Kinder	Kriegsmann	Denner
Rajan	Lynch*	Kuperman	Fisher
Sen	Miller[4]	Lavery	Glegg
Stoffa	Orr	Odom	Stanic
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Sutton	Porter	Schmidt	Wolf*
Yamamoto	Weller	Spofford[3]	
	Willemsen		
	Zhou[2]		

* Group Leader
1 Moves to Group III (*CRL*) and IV (*Clark 519*) on Thursday afternoon, April 25
2 Moves to Group I (*Carriage House*) on Thursday afternoon, April 25
3 Moves to Group II (*Clark 323A*) on Thursday afternoon, April 25
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16. Abstract (Limit: 200 words)

The results of an unclassified Workshop on Shallow Water Acoustics, sponsored by the Office of Naval Research Code 1125OA, are presented. The workshop was held on April 24-26, 1991 at the Woods Hole Oceanographic Institution and included about forty-five scientists specializing in ocean acoustics, geology, geophysics, and physical oceanography. The goal of the workshop was to determine future directions for basic research in shallow water acoustics. This report summarizes the recommendations of the workshop and includes a synopsis of the deliberations of four working groups which focused on the following specific research issues: (1) the seabed, (2) the water column and surface/Arctic, (3) analytic and numerical modeling/ambient noise, and (4) laboratory and field experiments/signal processing.

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